4.2.3. LONG-TERM TOTAL OZONE TRENDS

A new method was developed to investigate total ozone variations that are in the range of about 3.5 years to decades [*Harris et al.*, 2001]. The goal of the study was to create a trend line that is somewhat flexible so that the recent decreases as well as the (probable) recovery can be tracked. The method combines traditional total ozone trend-finding, i.e., autoregressive modeling (AR), techniques with trend analysis methods developed in CMDL by the Carbon Cycle Greenhouse Gases group. The intent was to first remove explained variations in the ozone. This step regresses total ozone to seasonal harmonics, the solar cycle, quasi-biennial oscillation (QBO) in equatorial stratospheric winds, detrended temperature at 100 and 500 hPa, and a cubic polynomial. The residuals of this fit are added back to the cubic function prior to the next step. Then a smooth curve is fitted to the resulting data according to methods of *Thoning et al*. [1989], with a filter chosen to remove periods in the data of fewer than about 3.5 years. The derivative of this smooth ozone "tendency curve" is the ozone growth rate curve. Integration of the growth rate curve gives the average growth rate. Uncertainties of the curves and the growth rate average are determined by bootstrap techniques.

First the method was applied to individual station data from the Dobson total ozone network. These data are archived at WOUDC in Downsview, Ontario, Canada. Figure 4.20a shows total ozone monthly means and the AR fit of explained variation for Bismarck, North Dakota. Figure 4.20b shows the total ozone tendency curve with 95% confidence limits for Bismarck. Residuals combined with the cubic function from the AR fit are also shown. Figure 4.20c shows the growth rate curve for Bismarck and the 95% confidence limits. Averaging the monthly values along this curve gives an overall growth rate of –1.4% decade^{-1} for the period December 1962 through December 2000. Bootstrap methods were used to determine a standard error (S.E.) of 0.2% decade^{-1}. For the individual stations examined, total ozone decreases ranged from 1 to 2% decade^{-1} since the 1960s and from 2 to 4% decade^{-1} over the period 1979-1997.

Figure 4.21a depicts the total ozone tendency curves for six midlatitude Dobson sites. The long-term total ozone decrease is clearly evident, with the ozone decline beginning in the early 1970s. Some of the stations share common features (peaks and dips). The common features in the ozone tendency curves are accentuated in the growth rate curves for the four similar midlatitude records (Caribou, Bismarck, Wallops Island, and Arosa) shown in Figure 4.21b. While keeping in mind that the exact locations of maxima and minima are somewhat uncertain because of the filtering process, it is noted that the coherence among these sites is maintained over their entire records. The growth rate curves for three tropical sites shown in Figure 4.21c also have coherence, although the pattern is different from that of the midlatitude curves. It is interesting to note that SMO’s pattern leads that of MLO by more than 1 year. The two sites are separated by only 15º of longitude but lie on opposite sides of the equator. The causes for growth rate coherence are not known, though widespread meteorological and dynamical patterns are possibilities [*Zerefos et al*., 1994; *Ziemke et al*., 1997]. Some consecutive cycles of the midlatitude growth rate curves match the solar cycle. This could be fortuitous or a hint at a possible secondary effect not accounted for by the fit to the solar index.

To further explore the total ozone growth rate coherence seen among the Dobson sites, CMDL obtained the TOMS/solar backscatter UV (SBUV) merged total ozone monthly data set (http://code916.gsfc.nasa.gov/Data_services/merged/). These data cover all longitudes, and latitudes from 60ºN to 60ºS. Data are gridded 5º of latitude by 10º of longitude and are available with few data gaps from November 1978 through December 2000. In the data set there are 24 × 36 grid cells, each of which can be thought of as a separate site with a time series consisting of 266 months of data. Each of the 864 time series was processed in the same way that the Dobson station data were processed earlier.

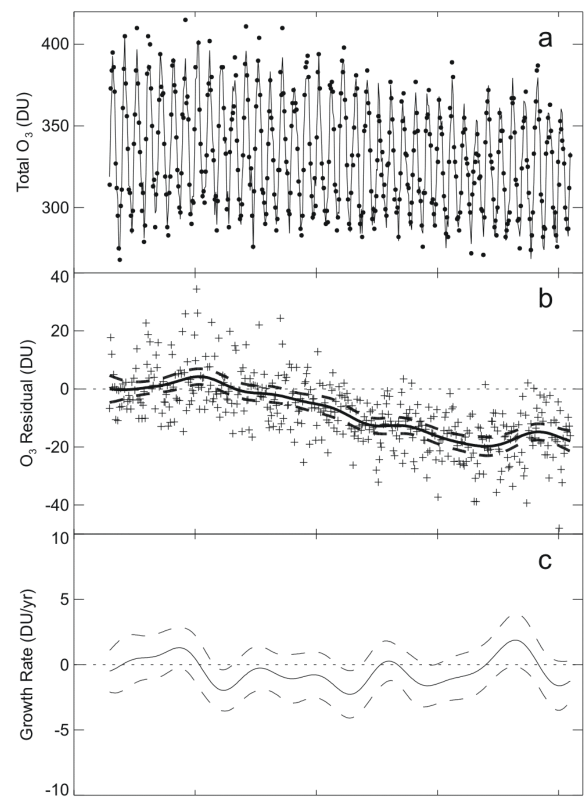

Fig. 4.20. Bismarck, North Dakota, total ozone data. (a) Ozone monthly means (filled circles) and the AR fit (solid line). (b) Total ozone tendency curve (solid curve) with 95% confidence limits (dashed curves). Residuals combined with the cubic function from the AR fit are shown as plus signs. The points and the tendency curve have been adjusted so that the tendency curve starts at zero. (c) The growth rate curve and 95% confidence limits.

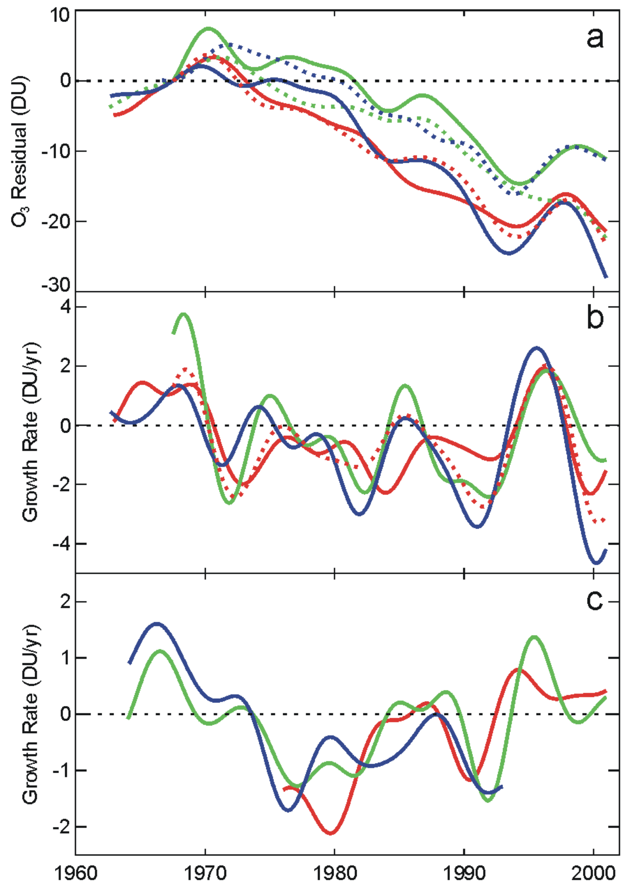

Fig. 4.21. Comparisons of total ozone tendency and growth rate curves. (a) Midlatitude tendency curves for Bismarck, North Dakota (solid red), Nashville, Tennessee (dotted green), Wallops Island, Virginia (solid green), Boulder, Colorado (dotted blue), Caribou, Maine (solid blue), and Arosa, Switzerland (dotted red). Tendency curves have been set to zero on July 1967 (the beginning of the shortest record) to aid the comparison. (b) Growth rate curves for four coherent midlatitude sites with the same colors as in (a). (c) Growth rate curves for the tropical sites, Samoa (red), Mauna Loa (green), and Huancayo (blue).

The results are compiled in Figure 4.22**,** which depicts the average growth rate in percent per decade over the entire grid. In this figure the cooler colors (green, blue, purple) denote relatively larger ozone decreases compared with the hotter colors (yellow, orange, red). In the area near the tropics that is cross-hatched in white, the total ozone growth rate is not statistically different from zero. The greatest ozone loss rate (or negative growth rate) in the southern hemisphere (SH) is centered at 0°E and 50-60°S (>8% decade^{-1}). This may be a result of some asymmetry of the Antarctic continent and the preferred pattern of vortex breakup after the ozone hole forms in the spring. The

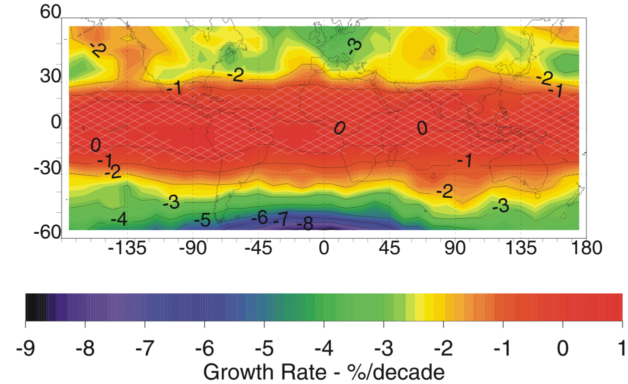

Fig. 4.22. The average total ozone growth rate in percent per decade for November 1978-December 2000.

greatest loss rates in the northern hemisphere (NH) occur over Western Europe, Great Britain, Siberia, and the North Pacific (>3% decade^{-1}).

The next step was to look at the total ozone time series averaged over 5°-latitude zones. Figure 4.23 shows the total ozone deviation since 1978. This plot is analogous to the total ozone tendency curves for the six sites shown in Figure 4.21a. Again hot colors signify relatively more ozone. This plot shows a steady decrease in the high latitudes of the SH. More than 35 DU of total ozone has been lost since November 1978 at 60°S compared with more than 15 DU at 60°N. The NH high midlatitudes have seen a slight recovery since the low point in 1995. The areal coverage of the region representing more than a 10-DU loss has increased from about 40° and poleward in 1988 to about 23° and poleward at the end of 2000.

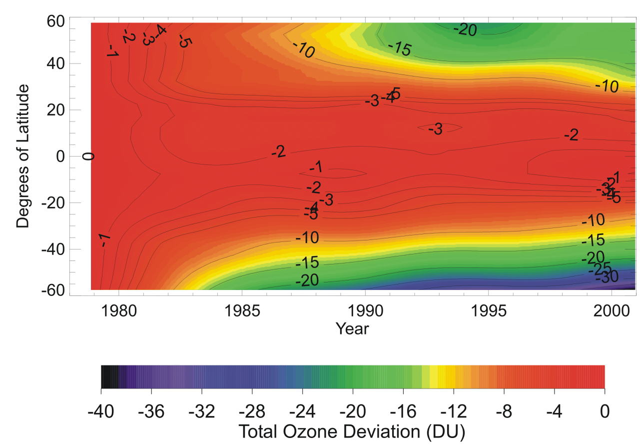

Fig. 4.23. The total ozone zonal deviation in percent per decade since November 1978.

Figure 4.24 shows the instantaneous zonal growth rate for 60°N-60°S. Seen in this plot are the growth rate evolution in time and the patterns of growth rate coherence. The instantaneous growth rate is not statistically distinguishable from zero over most of the warm colors (–2 to 2% decade^{-1}). Outside of this area, the largest loss rates (greatest negative growth rates) occurred in 1982, 1991, and 1999 in both hemispheres. The largest loss rates of the time series (>9% decade^{-1}) occurred in 1982-1983 in the most southerly latitudes. Events that may have contributed to this decrease are the El Chichón volcanic eruption, the declining phase of the solar cycle, and a very large El Niño event (peaking in early 1983). Loss rates in 1991-1992 were very likely influenced by the eruption of Mt. Pinatubo and possibly by the decline in the solar cycle. These reasons are not present during the high loss rates of 1999. It is interesting to note that the NH losses during 1982 and 1999 peaked at 30°N rather than at higher latitudes. Finally, during 1995-2000 there was a positive growth rate for ozone (>2% decade^{-1}) in the high northern latitudes. Warm temperatures in the stratosphere and boreal fires may have contributed to this effect.

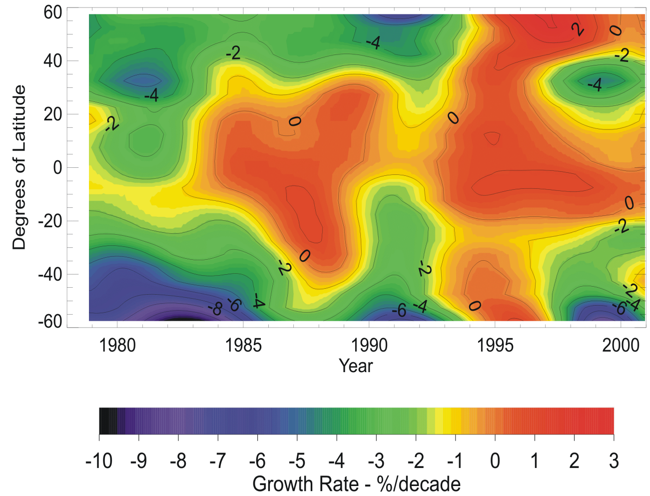

Fig. 4.24. The instantaneous zonal total ozone growth rate in percent per decade.